Light Attenuation in a Semitransparent Foam Sheet—Thickness Measurement for Industrial Use

Masahiro Ueda, Sanae Mizuno, Akio Matsumura

Faculty of Education, Fukui University, Bunkyo 3-9-1, Fukui 910, Japan

&

Fumio Tohjyo

Yamabun Electric Co., Ltd, 632-2, Nakano, Higashi-Osaka, Osaka 578, Japan

ABSTRACT

An optical method for measuring the thickness of heterogeneous materials has been studied. The method is based on the light attenuation theory. A complete system has been constructed in order to demonstrate the applicability of the present method for industrial use. The experimental set-up consists of semiconductor lasers, focusing lenses, photo-diodes serving as a power meter and a personal computer with an A/D converter for data acquisition. Averaging of numerous measurements is required in the present method because the heterogeneous cell structure of the foam material yields large fluctuations in transmitted light levels. The fluctuations can be reduced to below 1% of the transmitted light power by 80 times averaging. The error of the measurement is considered to be a few tens of micrometers in thickness. The present system is capable of sampling data at a rate of 400 Hz and has been successfully applied to a manufacturing process.

1 INTRODUCTION

Numerous optical sensors have recently been developed in response to the fact that small-size semiconductor lasers have become commercially available at a reasonable cost.[1] Although the application of these sensors and lasers involves a wide range of laws and theories in physics, Lambert's law is one of the most frequently used to estimate light attenuation. The law was successfully employed in a high sensitivity optical blood leakage detection system[2] and also in a dye concentration measurement system.[3]

In the present study, light attenuation has been used to measure the thickness of sheets of polyethylene foam and polystyrene. Polyethylene is widely used for a variety of products such as bath mats, packing sheets for shipping and heat insulators for building comfort. Polystyrene is mainly used for cups and hot food containers. The thickness of the foam sheet is important to the makers from the viewpoint of standardization of manufacture. The major difficulty in thickness measurement of foam sheets is caused by the heterogeneous cell structure of the foam, which can yield enormous fluctuations in the measured data depending on the measurement technique and on the sampling locations. An averaging method has been adopted for solving this difficulty and enables us to determine the thickness with good accuracy. A complete measuring system has also been constructed in order to demonstrate the suitability of the present method for industrial use.

2 PRINCIPLE AND METHOD

2.1 Principle

Figure 1 shows a fundamental illustration of a light attenuation process. Polyethylene or polystyrene foam consists of small cells filled with air. The light is scattered at each cell wall as it passes through the foam. The transmitted light intensity, I_t, is then given by the multiplication of the transmittance, T_k, on each cell surface in the measuring optical path, as follows:

$$\begin{aligned} I_t(\mathbf{x}) &= (T_N T_{N-1} \cdots T_k \cdots T_3 T_2 T_1) I_i, \\ &\equiv \mathbf{T}(\mathbf{x}) I_i, \end{aligned} \tag{1}$$

where I_i is the input light intensity and N the number of the cell surface along the optical path. In particular, T_1 shows the transmittance on the surface of the foam sheet. The transmittance, T_k ($k = 1, 2, \cdots$), and the total number, N, are then a function of an irradiated position $\mathbf{x}$, as shown in Fig. 1a. Thus, the output, i.e. transmitted light intensity, depends on the position.

We expect, however, that the output light intensity after passing through an optical path d, I_d, follows Lambert's law[5] if a sample is uniform, as given by

$$I_d = I_i \exp(-\alpha d),$$

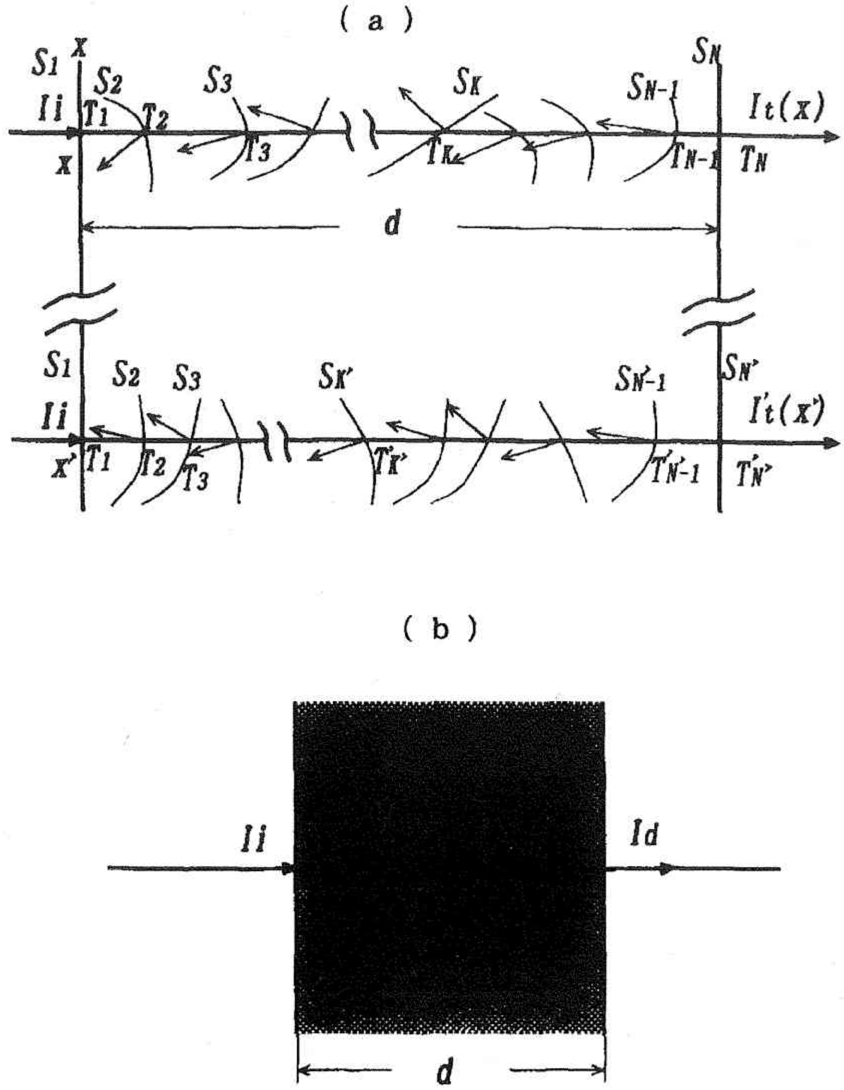

Fig. 1. Light attenuation in a foam sheet from the microscopic viewpoint (a) and from the macroscopic viewpont (b).

or

$$\ln (I_d/I_i) = (-\alpha)d, \tag{2}$$

where α is an absorption coefficient. This is an approximate expression for light attenuation from a macroscopic viewpoint. That is, the output intensity, I_d, is considered to be the mean value of $I_t(\mathbf{x})$ for many sampling points around the measuring point.

As is shown in the following section, the mean values of $T(\mathbf{x})$, $\langle T(\mathbf{x})\rangle$, at each measuring point $\mathbf{x}$, are approximately equal and we can then assume

$$\langle \mathbf{T}(\mathbf{x})\rangle \fallingdotseq T^N. \tag{3}$$

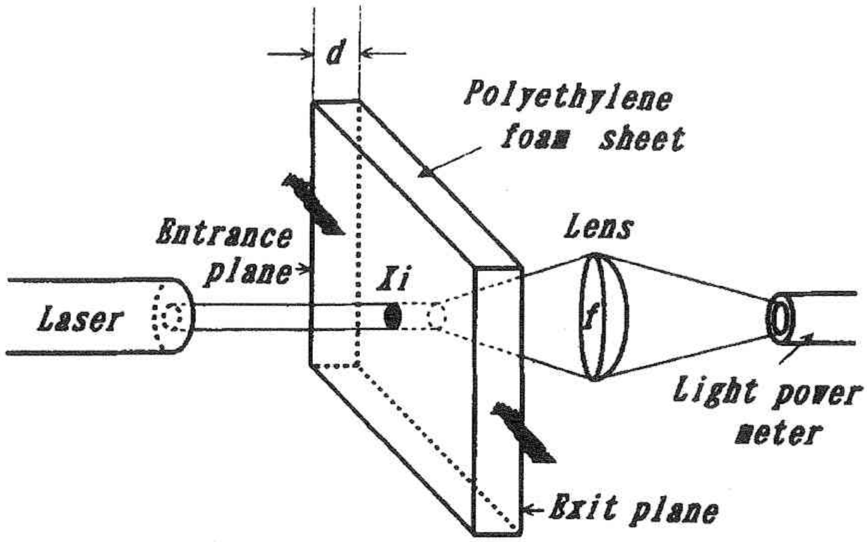

Fig. 2. Fundamental optics of the experimental set-up.

Equating eqns (1) and (2), and using the relation given in eqn (3), we obtain the following relation:

$$N/d = -\alpha \log e/\log T. \tag{4}$$

Equation (2) gives us information on the thickness and eqn (4) on the cell density, N/d or the cell transmittance.

2.2 Method

Figure 2 shows the experimental set-up for a measurement. Laser light of wavelength 670 nm from a semiconductor laser passes through a polyethylene foam sheet. The transmitted light diverges by scattering in the foam and is focused on a light power meter. The light power, I_d, is processed by the data acquisition system shown schematically in Fig. 3.

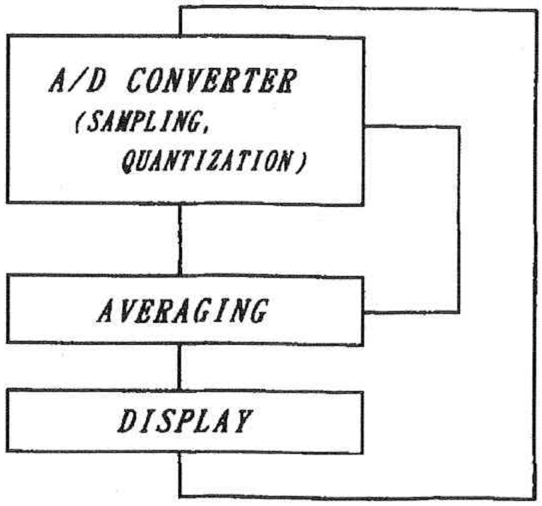

Fig. 3. Block diagram of the data acquisition and processing system.

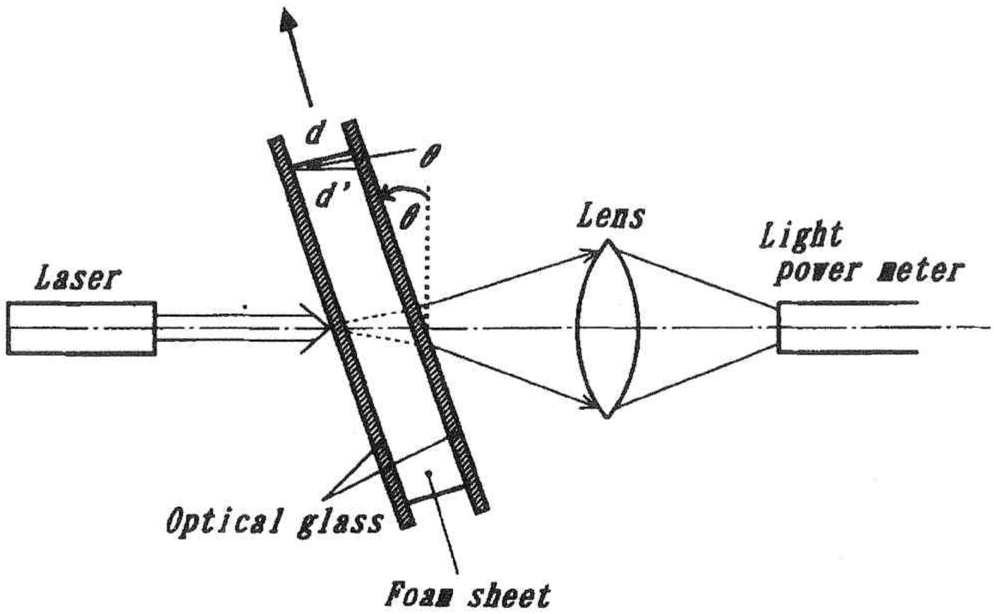

Fig. 4. Optics to measure the effects of compression and inclination of a semi-transparent foam sheet.

The continuous analog signals of I_d are sampled, digitized and stored in a computer memory. Results are given in the form of curves after smoothing. The resolution of the data acquisition system is 12 bits and the sampling rate is about 400 Hz.

Figure 4 shows a particular experimental set-up to measure the effect of cell structure on the transmittance, e.g. light attenuation. The polyethylene foam sheet is placed between a pair of transparent optical glass plates, slightly inclined to the normal to the laser beam. The thickness of the sandwiched foam sheet, *d*, is changed by compressing the glass plate. The optical path length through the sheet foam is thus changed by the compression of the glass plate or its inclination.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Results

Figure 5 shows an example of the transmitted light power at each measuring point. As shown, each data point differs to a great extent from the mean value, the range of which reaches 70%. This is attributed to the difference of total transmittance, $\mathbf{T}(\mathbf{x})$, along each optical path, as shown in Fig. 1a. T_l may be the major factor. The difference can, however, be reduced by smoothing, i.e. averaging. Two technical methods, both of which are based on the same principle, are

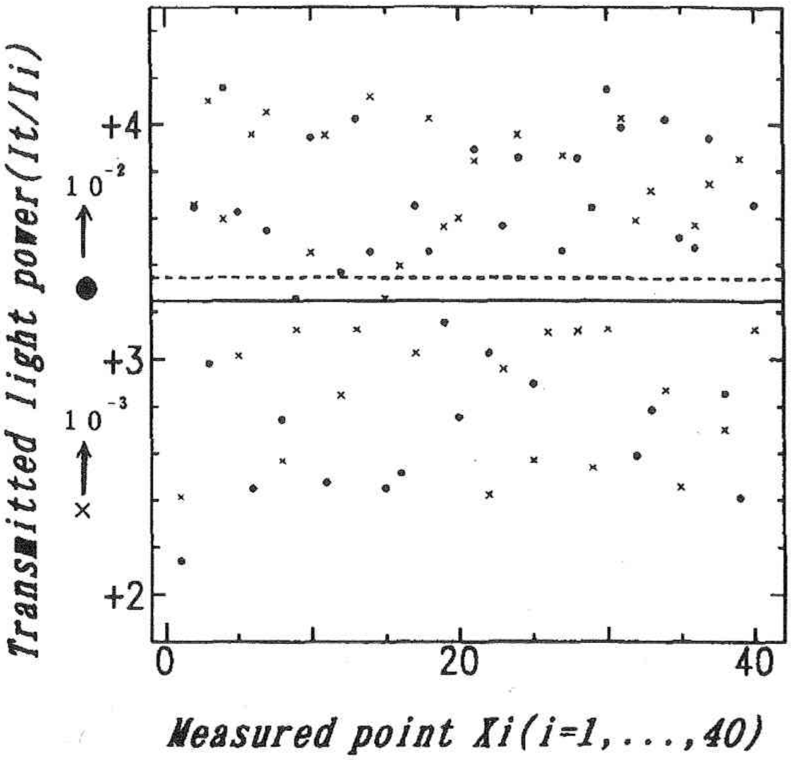

Fig. 5. Transmitted light power at each point. (●) $d_1 = 2{\cdot}76$ mm; (×) $d_2 = 5{\cdot}58$ mm. (- - -) Mean value of $3{\cdot}35 \times 10^{-3}$ for $d_2 = 5{\cdot}58$ mm; (—) mean value of $3{\cdot}24 \times 10^{-2}$ for $d_1 = 2{\cdot}76$ mm.

available for this smoothing. One is to enlarge the spot size of the laser irradiation. This method, however, necessitates the use of a large focusing lens and further to cut an ambient light off to a very small amount. The other method, used in this study, is to make many measurements around a small region.

The smoothing effect is shown in Fig. 6. As shown, smoothing over 80 points restricts the fluctuation of the mean value within a range of 1%. All the data except one example given in Fig. 5 were averaged over 80 points.

Figure 7 shows an example of the relation between transmitted light power and foam thickness. It can be seen that the transmitted light power decreases exponentially with the thickness. A straight line can be obtained by the method of a least mean square fit. The gradient of the straight line gives the absorption coefficient, α, in eqn (2). The value depends only on the property of the material used. A value of the thickness, d, has to be known for a determination of absorption coefficient, α, and should be measured by another method, e.g. the gage method.

In applying the method practically, the absorption coefficient, α, has to be determined repeatedly for each product.

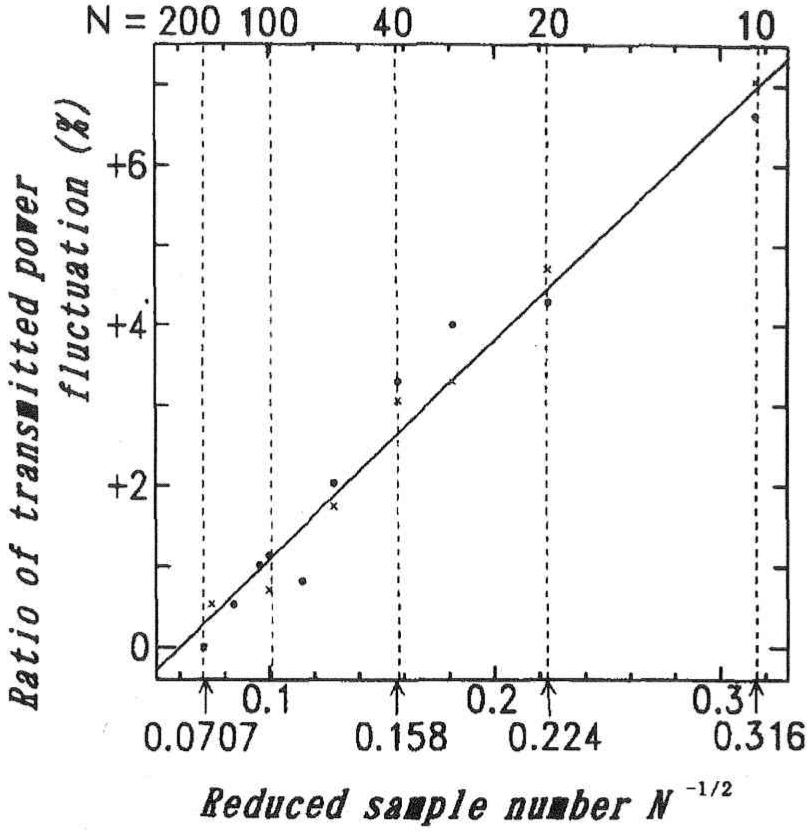

Fig. 6. Relation between the transmitted light power fluctuation (%) and the reduced sample number.

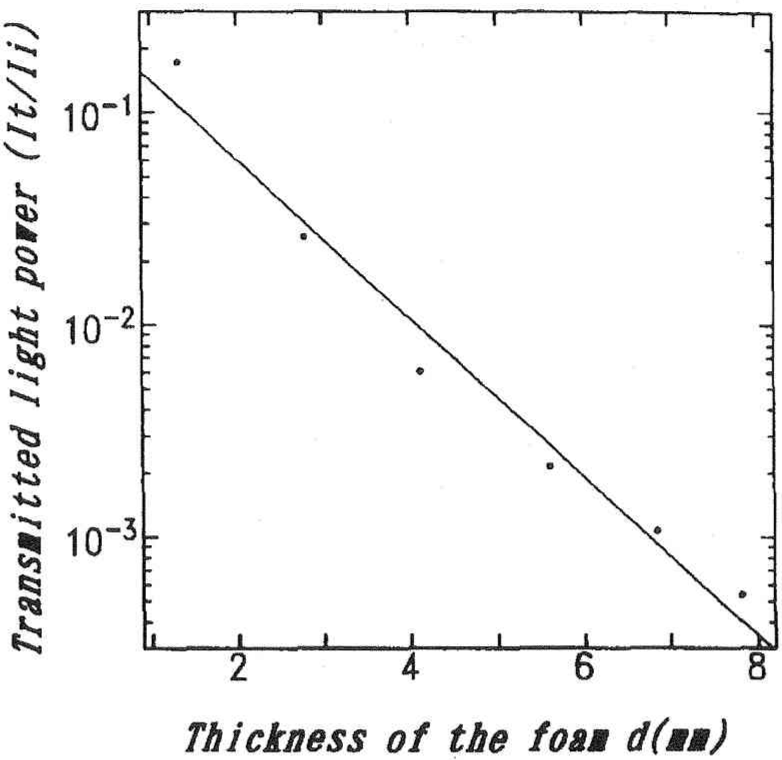

Fig. 7. Relation between the averaged light power and the foam thickness d.

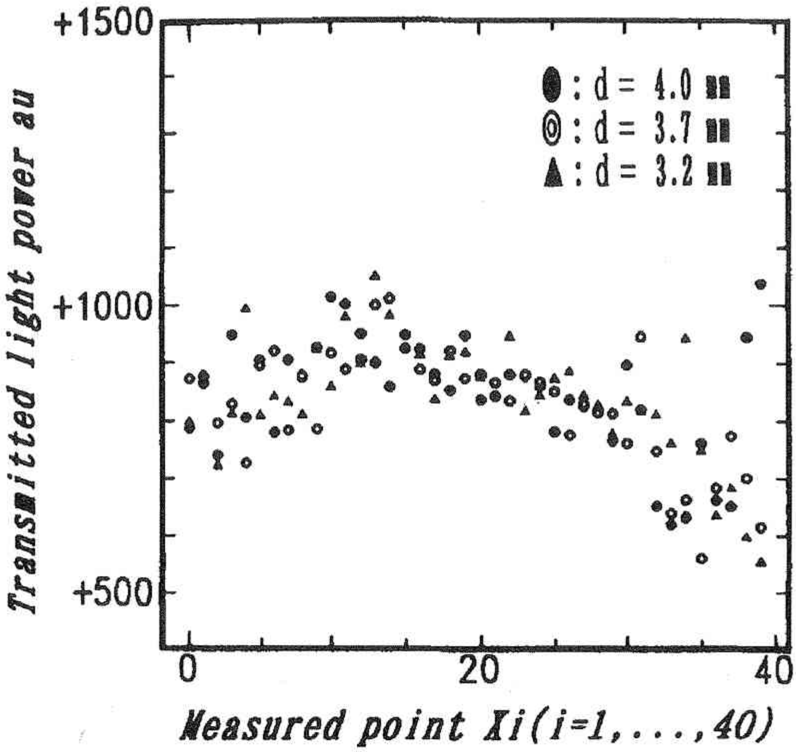

Fig. 8. Transmitted light power under squeezing. (●) Normal foam sheet; (◎), (▲) squeezed foam sheets. Each datum is an averaged value over 80 points in the vicinity of each other.

3.2 Discussion

The effect of the cell structure on the transmitted light power was examined using the optical arrangement shown in Fig. 4, where the optical path length is changed. The numbers of cell surfaces remained constant when we compressed the foam sheet and so the transmitted light power may be assumed unchanged.

Figure 8 shows an example of the effect of sheet compression on the transmitted light power. As expected, the transmitted light power was almost the same for each compressed foam sheet, i.e. $d = 3{\cdot}7$ mm and $d = 3{\cdot}2$ mm. This implies that each cell surface has an equal transmittance and that the total transmittance through the optical path depends on the transmittance of the material and the number of cell surfaces. That is, the assumption in eqn (3) is justified.

The optical path length increases when the normal of the foam sheet is inclined to the optical axis, and then the transmitted light decreases. In this case, the foam thickness, d, has to be replaced by $(d/\cos\theta - 1)$, as shown in Fig. 4. Figure 9 shows the effects on the transmitted light power, where the abscissa shows reduced inclination, $1/\cos\theta - 1$. This figure also implies the validation of eqn (3).

The accuracy of this method depends on the linearity between the

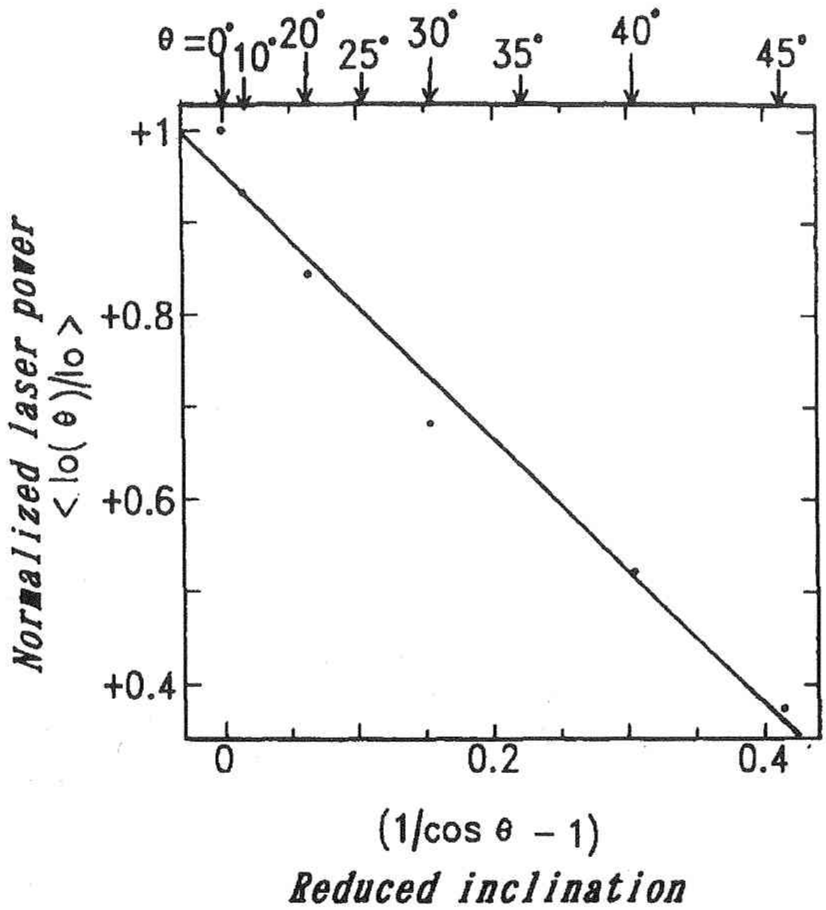

Fig. 9. Effect of inclination on the transmitted light power. The ordinate shows the light power normalized by the one for $\theta = 0$ and the abscissa the reduced inclination $(1/\cos\theta - 1)$.

thickness and the decrease in the transmitted light power, as shown in eqn (2). The light fluctuation due to ambient light introduces errors. It is very difficult to discriminate laser light from ambient light, but it is easy to reduce the effect of ambient light. Two methods are available. One is to use a pulsed laser of high peak power, but this is too expensive for our purpose. The other is to cover the laser light receiving system with a proper cylinder case. This can reduce the ambient light power below 0·05% of the maximum power of the transmitted laser light.

4 PRACTICAL APPLICATIONS

In practical foam production, molten polyethylene in an extruding machine is squeezed out from a circular arc air nozzle and is foamed to a sheet. The circular nozzle is divided into a few small portions, each of which has a nozzle aperture which can be controlled independently.

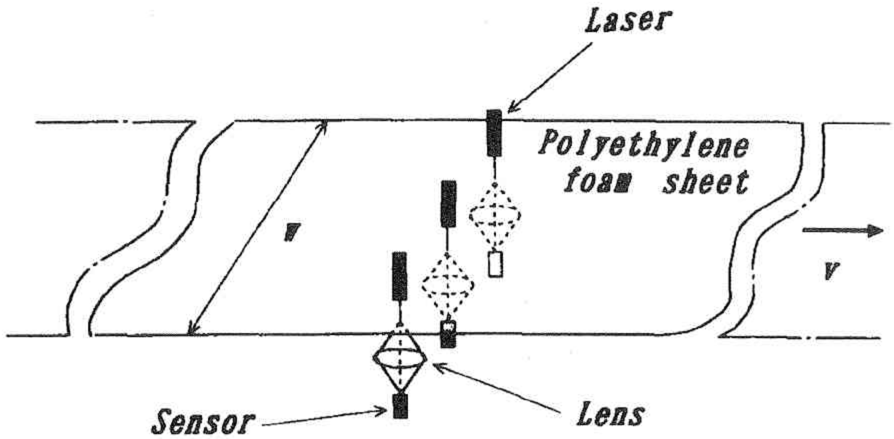

Fig. 10. Optical system for practical use.

The speed of output of the sheet is about 1–2 m/s and its width is about 2 m. The usual gage method of picking up contact elements is therefore difficult. Furthermore, it can only measure the thickness at both edges of the sheet. On the contrary, the present optical method may solve the above disadvantages simultaneously. Figure 10 shows an example of the practical optical set-up for the measurement. One optical sensor is desirable for each nozzle, where a sensor signal is processed to control the nozzle aperture. All the sensor signals from each sensor are processed on the computer simultaneously. The thickness of each portion along the width can thus be adjusted to the same thickness. Figure 11 shows an example of the results. The sampling rate of this system was about 400 Hz. The production speed of the foam sheet was 1·5 m/s. As discussed above, one datum was given as the average of 80 points and then the average along a 30 cm length. The spot size of the laser was about 5 mm in diameter at an irradiated surface and then each sampling point slightly overlapped each other. The deviation of the thickness was found to be within 0·01 mm over 300 m from this figure. The deviations on other portions in the width direction were kept within this range.

Figure 12 shows another example of the measurement. This is a result given by the system developed for the precise measurement for a food container. The foam sheet for a food container was produced with relatively slow speed of about 10 cm/s. Each sampling point was overlapped close together. That is, each datum was not an average over totally different points but over locally common points. The result by the usual gage method is also shown for the comparison. Both results agreed quite well within a deviation of 20 μm. From the result, the error of the method in this study is supposed to be within a few tens of micrometers.

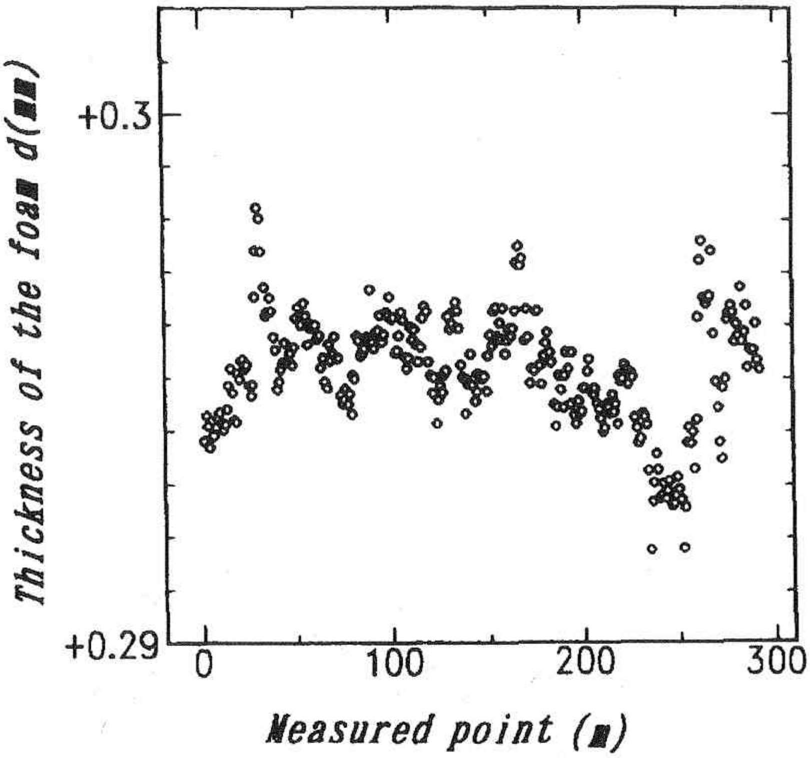

Fig. 11. Thickness of the polyethylene foam sheet measured in the manufacturing process. Each datum was plotted at intervals of 3 m and total length was 300 m.

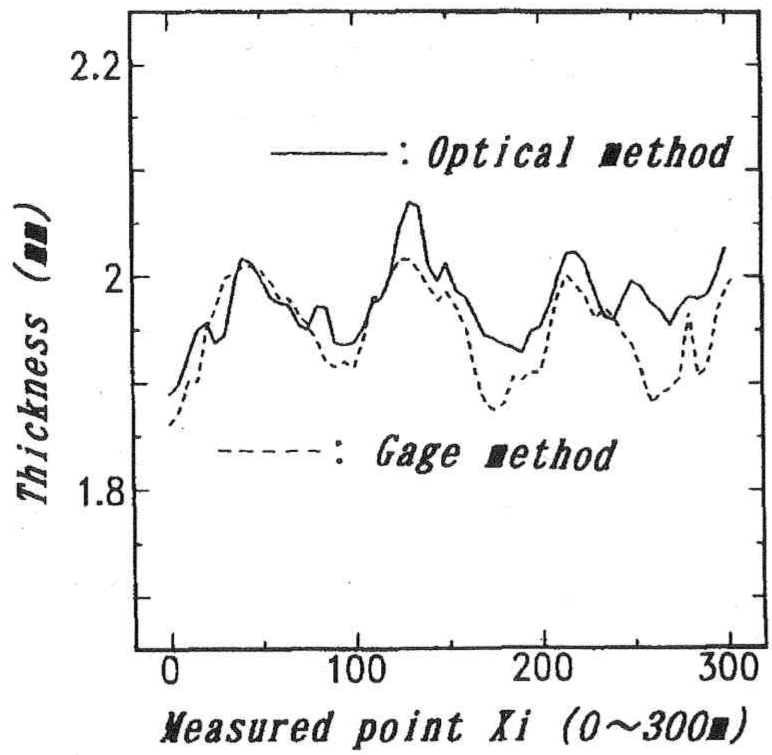

Fig. 12. Thickness of the polystyrene foam sheet measured in the manufacturing process.

5 CONCLUSION

The optical method has been developed for the thickness measurement of foamed sheets of polyethylene and polystyrene which have heterogeneous cell structures. Light attenuation was used in the measurement and averaging enabled us to determine the thickness in spite of large fluctuations in measured data due to the heterogeneous structure of the sheets. The error of the measurement is a few tens of micrometers. Since the present method provides an instantaneous and continuous measurement, automatic thickness control can be accomplished in the manufacturing of these sheets, which is not feasible by the conventional gage method, enabling us to eliminate or reduce labor costs in manufacturing.

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